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The Effects of Volcano-Induced Ozone Depletion on Short-Lived Climate Forcing in the Arctic

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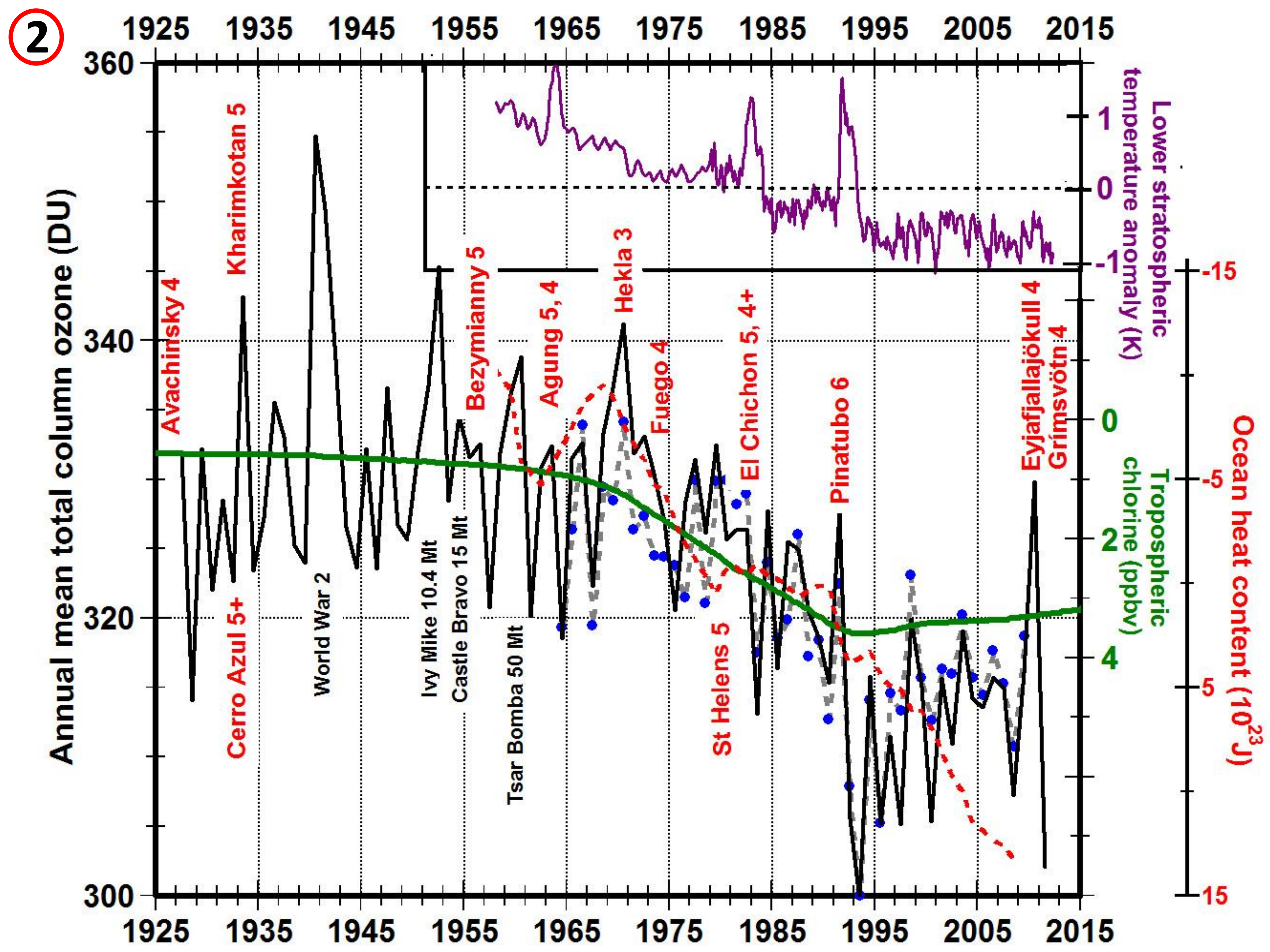
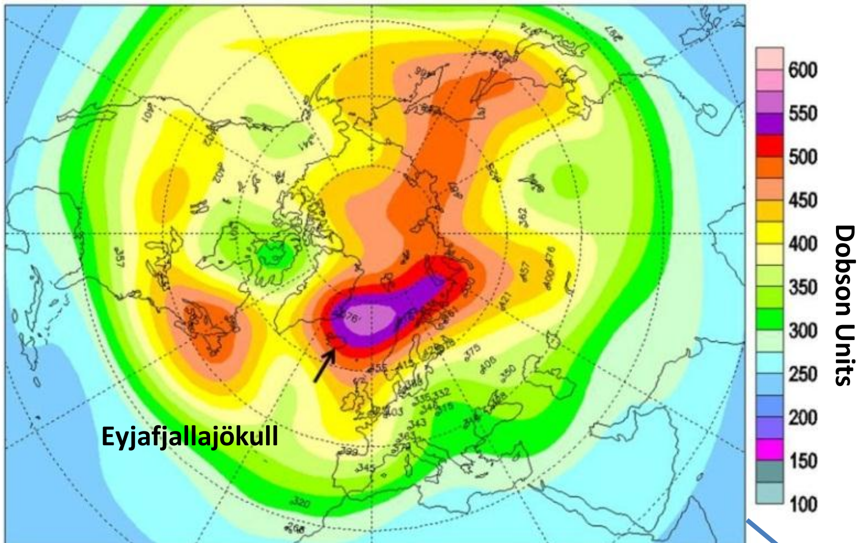

2
1925
1935
1945
1955
1965
1975
1985
1995
2005
2015
360
340
320
300
Annual mean total column ozone (DU)
Lower stratospheric temperature anomaly (K)
1
0
-1
Tropospheric chlorine (ppbv)
0
2
4
Ocean heat content (10^{23} J)
-15
-5
5
15
Avachinsky 4
Kharimkotan 5
Cerro Azul 5+
World War 2
Ivy Mike 10.4 Mt
Castle Bravo 15 Mt
Tsar Bomba 50 Mt
Bezymianny 5
Agung 5, 4
Hekla 3
Fuego 4
St Helens 5
El Chichon 5, 4+
Pinatubo 6
Eyjafjallajökull 4
Grímsvötn 4

③ Annual Mean Total Column Ozone

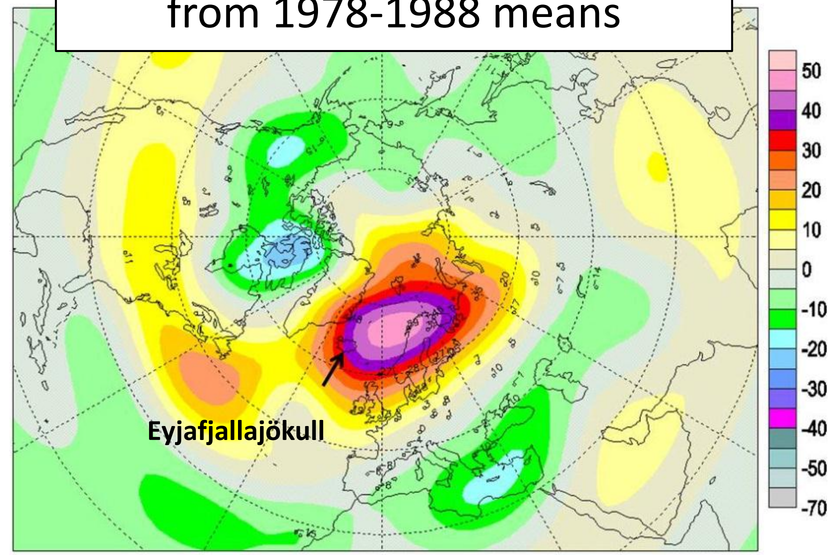
- Longest measurements have been at Arosa, Switzerland, since 1927
- The Arosa data (black line) are very similar to the annual mean area-weighted total ozone deviation from the 1964-1980 means for northern mid-latitudes (30°N-60°N) (dashed gray line, blue data points) (WMO Scientific Assessment of Ozone Depletion, 2010)
- Anthropogenic tropospheric chlorine (green line) depleted ozone ~3% (Solomon, 1999)
- Eruption of Pinatubo increased ozone 2% in 1991 , but decreased it 8% in 1992
- Similarly for Icelandic basaltic volcanoes Eyjafjallajökull (2010) and Grímsvötn (2011) and most earlier eruptions
- Long-term depletion of ozone was synchronous with
  - Cooling of lower stratosphere ~2°C (purple line)
  - Increase in annual mean height of the troposphere by ~160 m
  - Warming of the upper troposphere ~0.1°C
  - Increase in mean surface temperatures ~0.5°C
  - Increase in ocean heat content (dashed red line)

4 Ozone Increase Before Eyjafjallajökull Eruption

Total column ozone for Feb 19, 2010



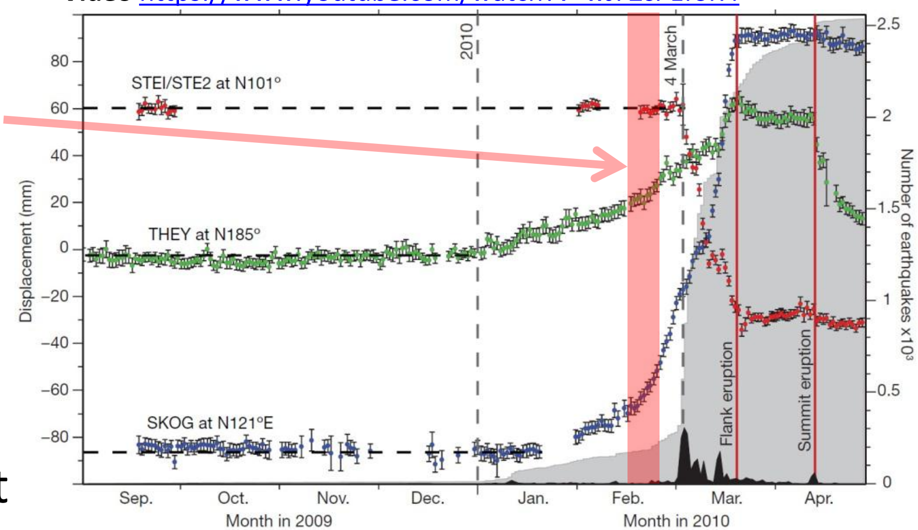
Mean deviation Feb 20-28, 2010 from 1978-1988 means



Environment Canada. *Archive of world ozone maps*
exp-studies.tor.ec.gc.ca/clf2/e/ozoneworld.html

- Ozone increased on February 19-26, 2010, just as surface deformation and earthquakes showed magma started moving up from 4-6 km depth
- Flank eruption began March 20
- Summit eruption began April 14
- Magma is in a reductive state so it is unlike to contain ozone
- Source of the ozone is not clear
- Similar before Pinatubo but less direct due to the Brewer-Dobson circulation

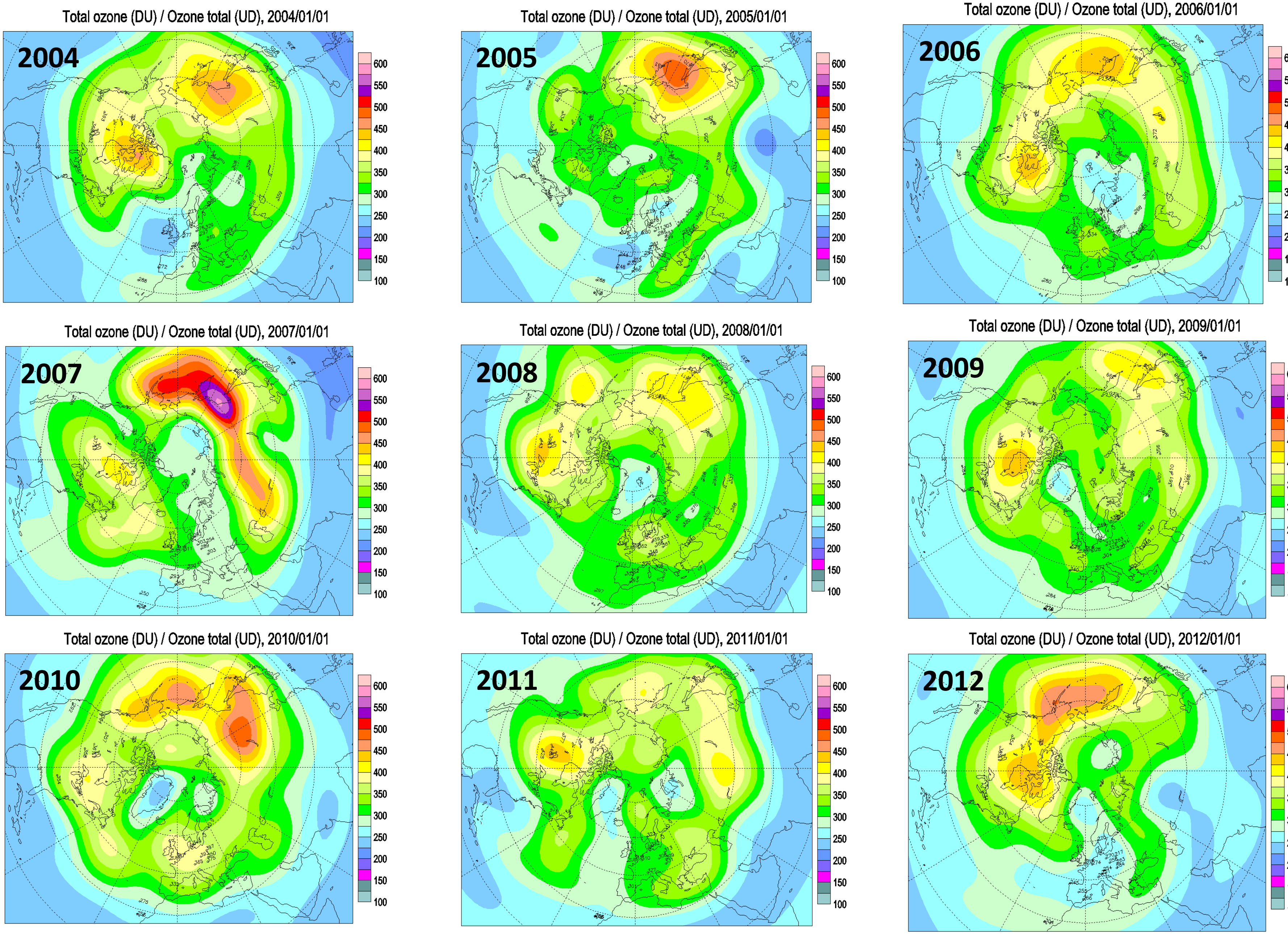
Video https://www.youtube.com/watch?v=wJFZcPEfoR4



Base figure from Sigmundsson et al., Nature 468:426,2010

⑤ Ozone Column Is Always Varying

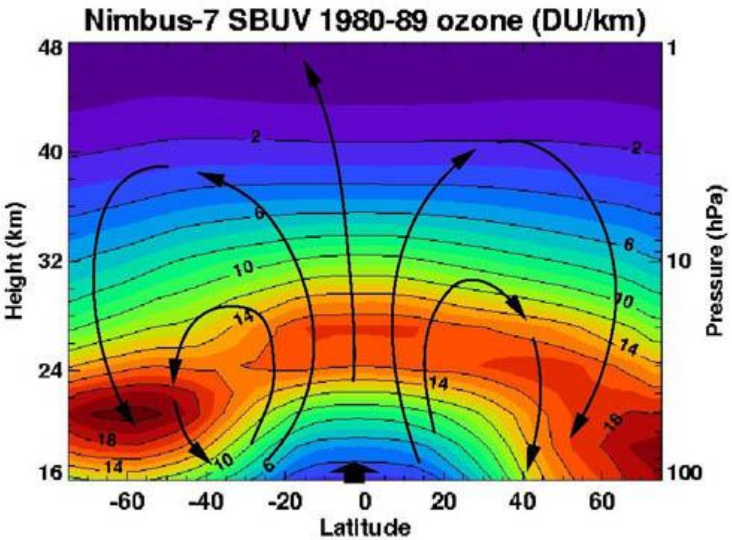
Each January first



⑥ Photodissociation of Ozone Warms the Atmosphere

- Photodissociation is the most effective way to convert electromagnetic radiation into temperature because all of the energy absorbed to break a molecular bond is converted into translational kinetic energy of the two separating atoms or molecules and, according to the kinetic theory of gases, the temperature of a gas is equal to the average translational kinetic energy of all of its atoms and molecules times a constant
- Depletion of ozone moves this warming from the lower stratosphere down into the troposphere and to Earth
- "From the time of Dobson's early measurements in the 1920s, it has been known that the total ozone amount undergoes large day-to-day fluctuations" (Reed, 1950) in the mid to high latitudes where the Brewer-Dobson circulation brings stratospheric ozone formed mostly in the tropics down into the lower stratosphere and upper troposphere

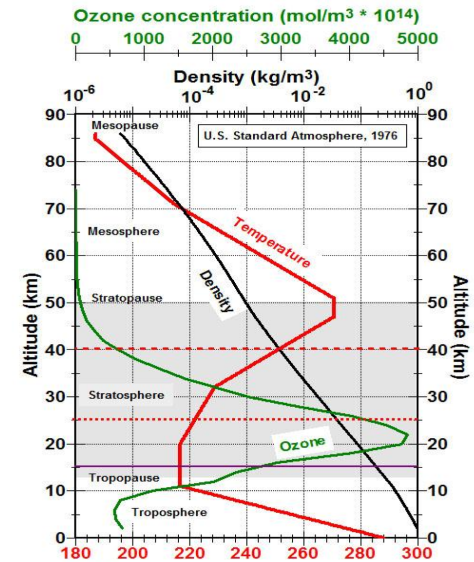
Brewer-Dobson circulation



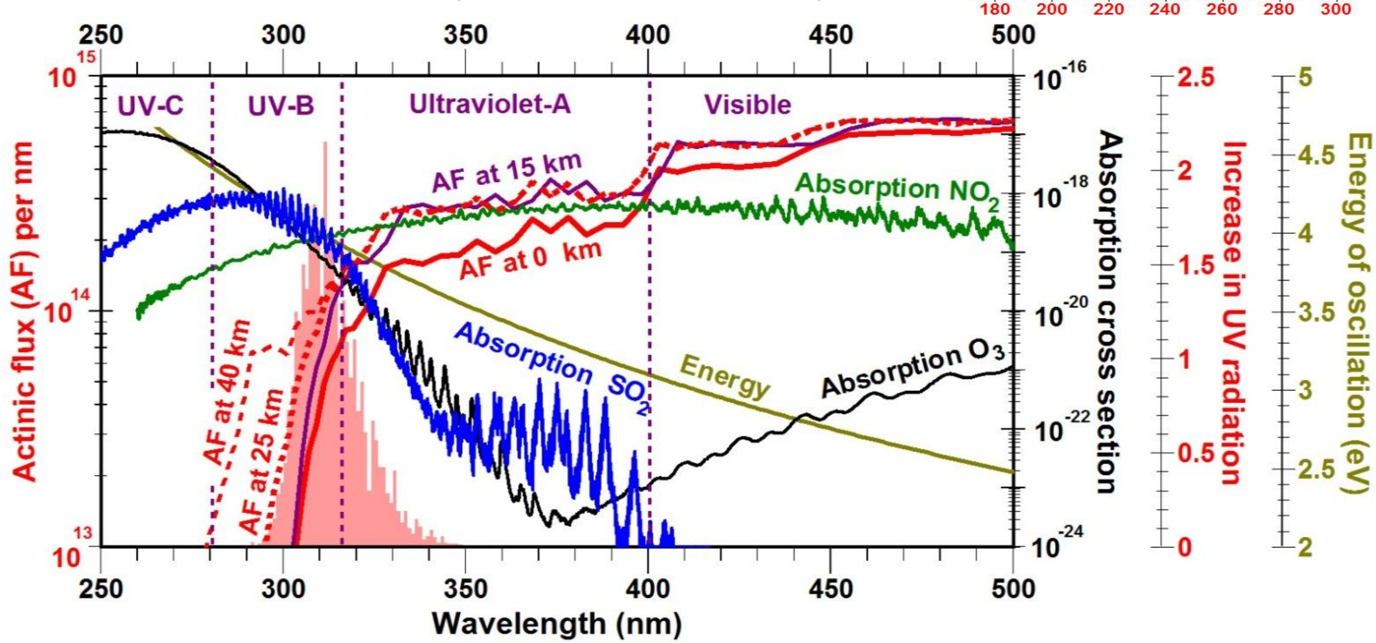
- There is a strong correlation between column ozone and meteorological conditions such as atmospheric and surface temperatures and the resulting depth and location of surface pressure highs and lows (Fioletov, 2008)
- Very small amounts of ozone are important because the photodissociation of ozone and its recombination are catalytic processes that typically occur over and over, converting electromagnetic energy into temperature while not necessarily changing the amount of ozone

7 The Ozone Column Determines How Much Solar Ultraviolet Energy Reaches Earth

- UV with wavelength <242 nm photodissociates oxygen
- UV with wavelength <340 nm photodissociates ozone
- Photodissociation heats the stratosphere efficiently
- Actinic flux (AF) shows how much of these wavelength are filtered out in the stratosphere



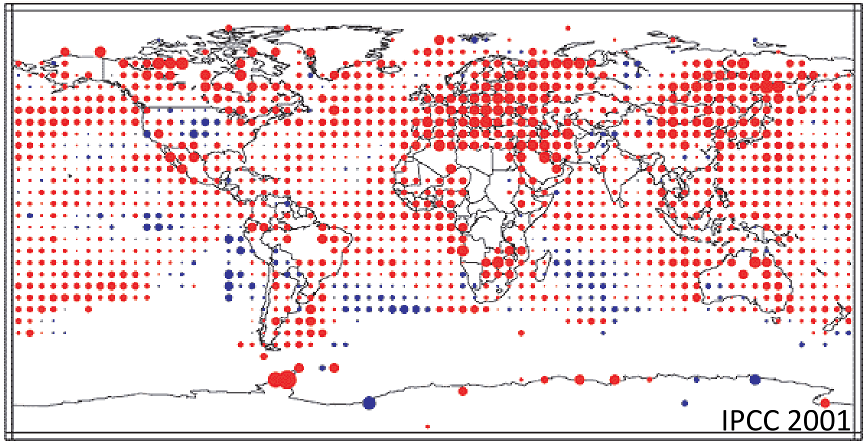
- A 30% decrease in ozone column allows an increase in solar flux of 1 W m^{-2} in a narrow wave band (red shaded area) to reach Earth for overhead sun and 0.28 W m^{-2} for solar zenith angle of 70^{o} (Madronich, 1993)



8 The Greatest Global Warming Is At The Times and Locations of the Greatest Ozone Depletion

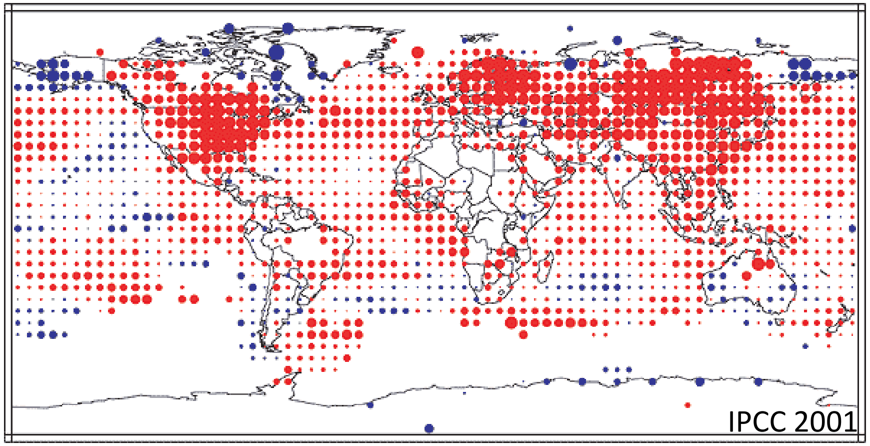
Winter Southern Hemisphere

(c) JJA temperature trends, 1976 to 2000



Winter Northern Hemisphere

(a) DJF temperature trends, 1976 to 2000



On the Antarctic Peninsula

- Minimum monthly temperature up 6.7°C from 1951 to 2003
- 87% of marine glaciers retreated
- 7 larger ice shelves break free
- surface temperatures of Bellingshausen Sea rose 1°C
- Circumpolar Deep Water of Antarctic Circumpolar Current warmed

In the Arctic

- Unprecedented ozone depletion in 2011 >80% at altitudes of 18-20 km
- Extent of Arctic sea ice decreasing >11% per decade
- Average snow-covered area decreased ~7% primarily since 1982
- Loss of ice in Greenland has been accelerating at a rate of 21.9 Gt/yr^2

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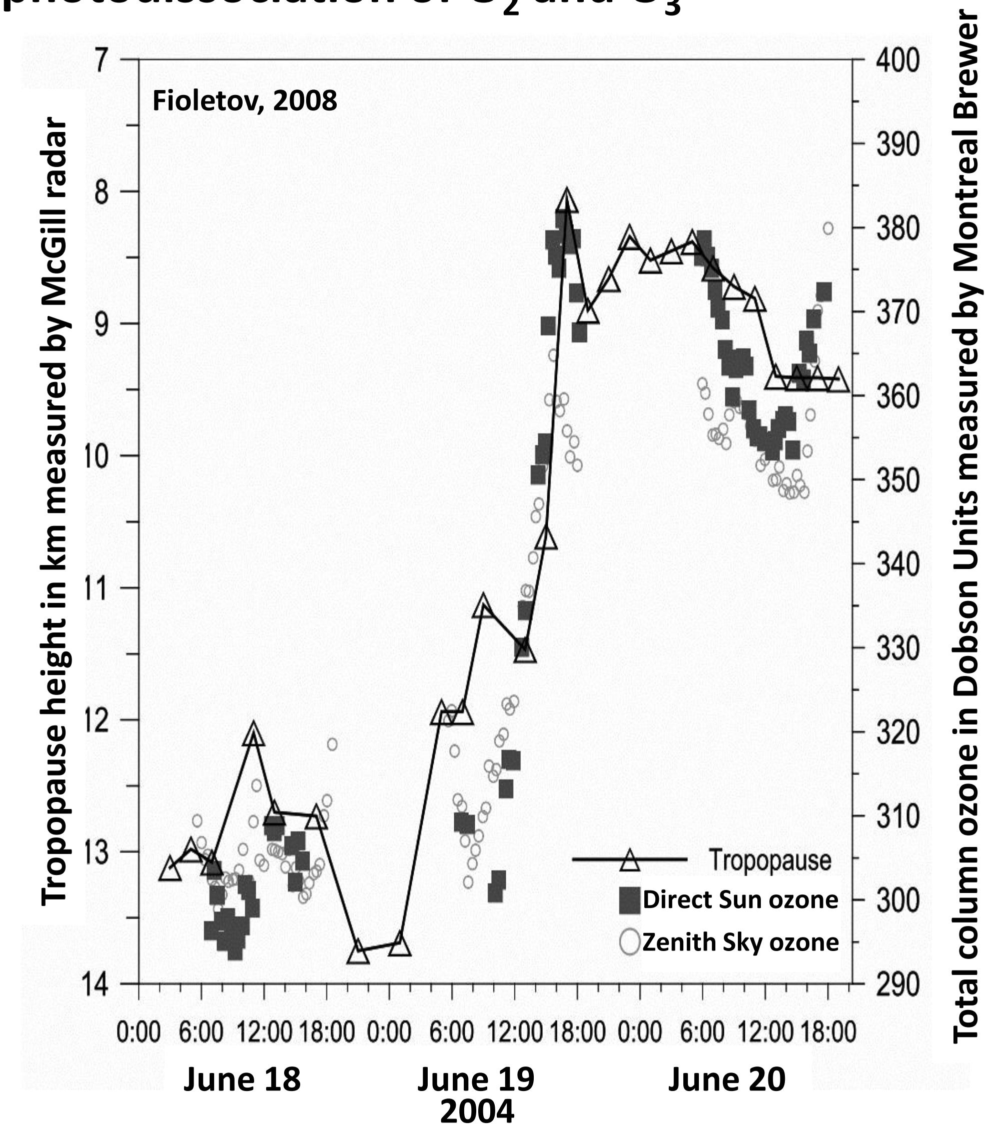
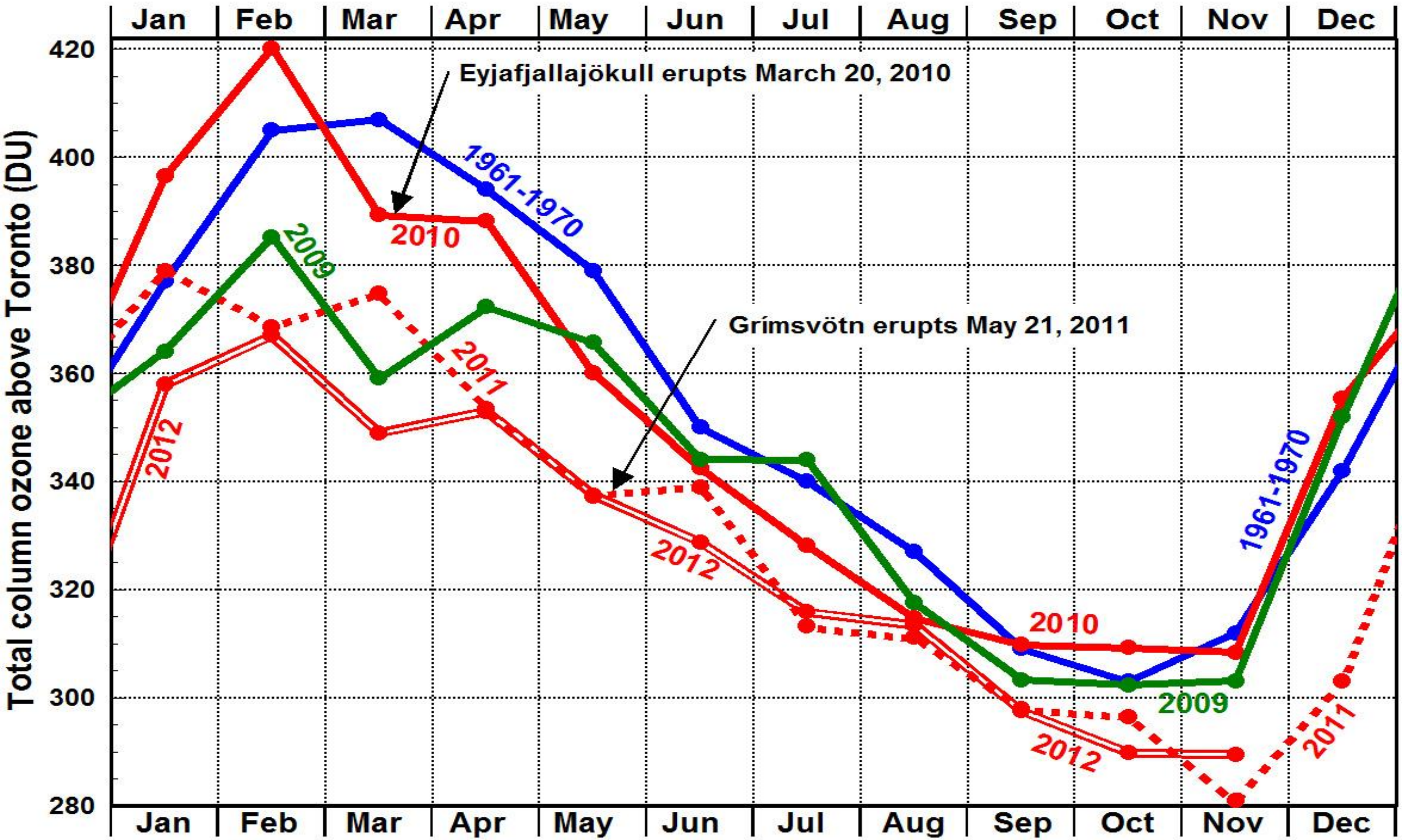
The Tropopause is a Very Dynamic Boundary

between the troposphere heated by a sun-warmed earth and the stratosphere heated by solar ultraviolet radiation energetic enough to cause photodissociation of O_2 and O_3

- The average height of the tropopause varies from 16.6 km in the tropics to 9 km near the poles
- The height of the tropopause above Montreal, Canada, fell 5 km in 6 hours as total column ozone increased 20% →
- Annual mean tropopause heights increased ~160 m between 1980 and 2004 (Seidel et al., 2006) while the lower stratosphere cooled ~2°C, the upper troposphere warmed ~0.1°C and mean surface temperatures in the northern hemisphere rose ~0.5°C

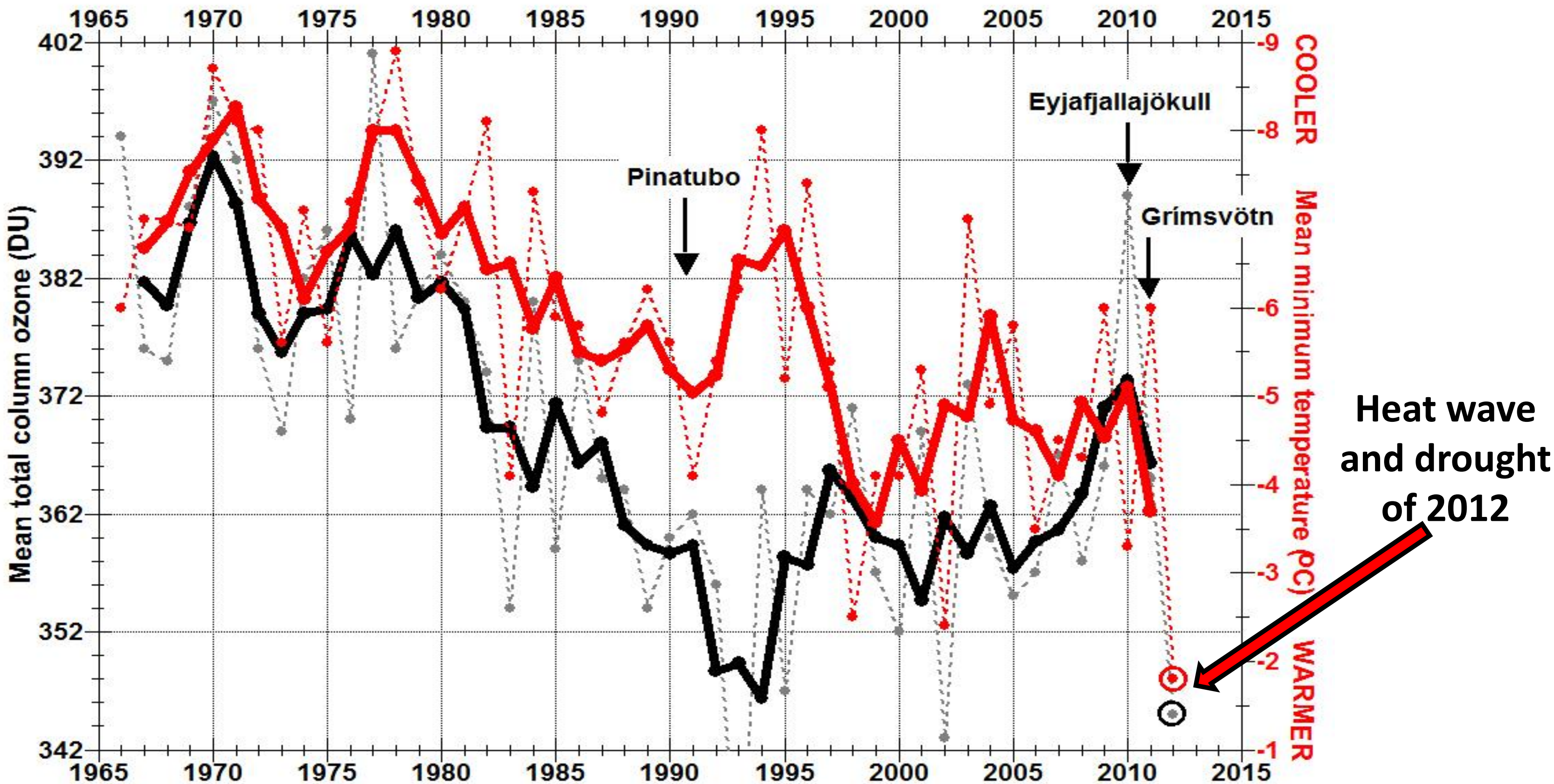


10 Ozone Depletion was Especially Strong in 2011-2012



- Monthly mean total column ozone above Toronto, Canada, in November, 2011, was 12% below the average for Novembers in 1961 through 1970 and has remained unusually low throughout 2012

11 Less Ozone ➡ Lower Temperatures in Stratosphere Higher Temperatures on Earth



- When mean total column ozone measured during the months of December through April in Toronto Canada (black line) decreases, mean minimum temperature for the same months **typically** but not always warms (red lines, y-axis inverted) except when the Pinatubo aerosols caused cooling.

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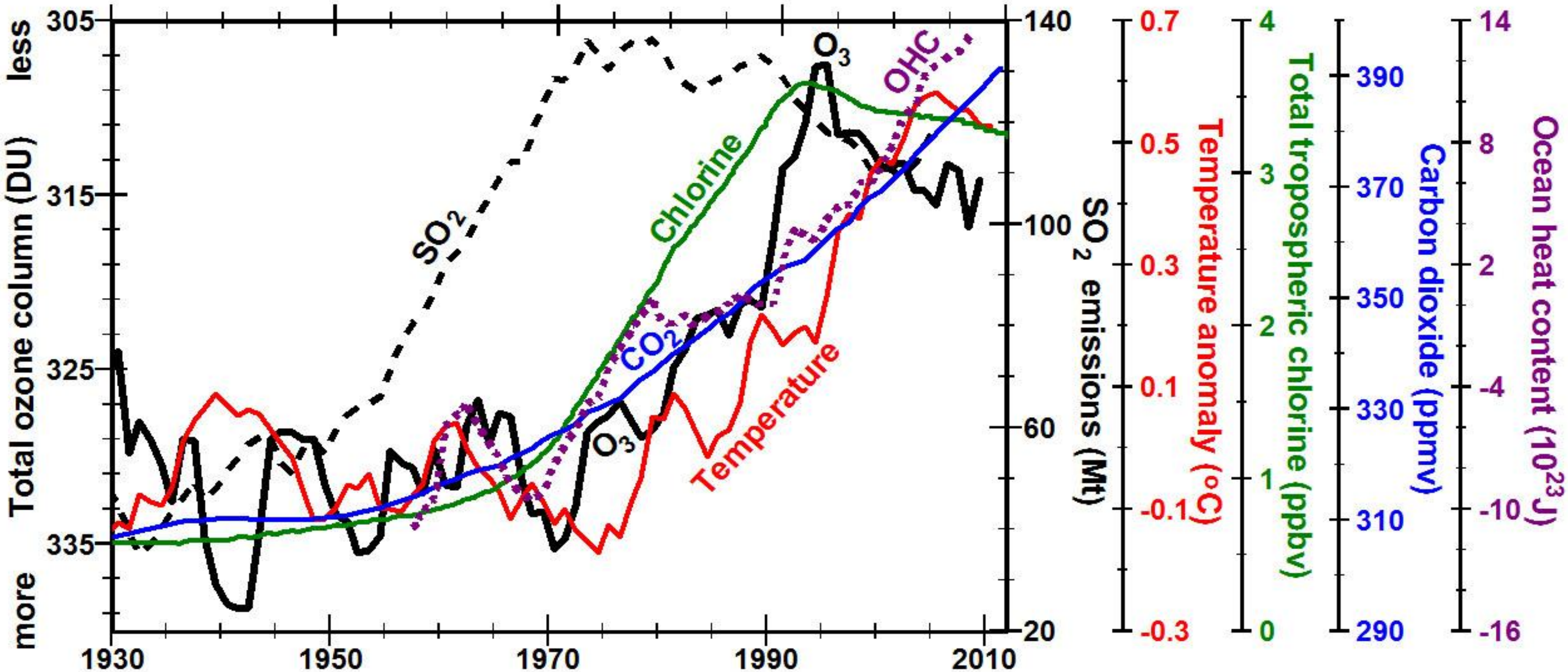
Warming Followed Ozone Depletion, Not Increased Pollution



- The primary time delay in the atmospheric system involves the heat capacity of the ocean
- Increasing ocean surface temperature ~5 years after decreasing ozone is within the likely time range calculated by Hansen et al. (*Science* 229:857, 1985)
- From 1976, when ocean heat content began increasing, the annual rate of increase of CO_2 doubled and even quadrupled
- Increase in SO_2 was 30 years before warming; unlike to have caused warming

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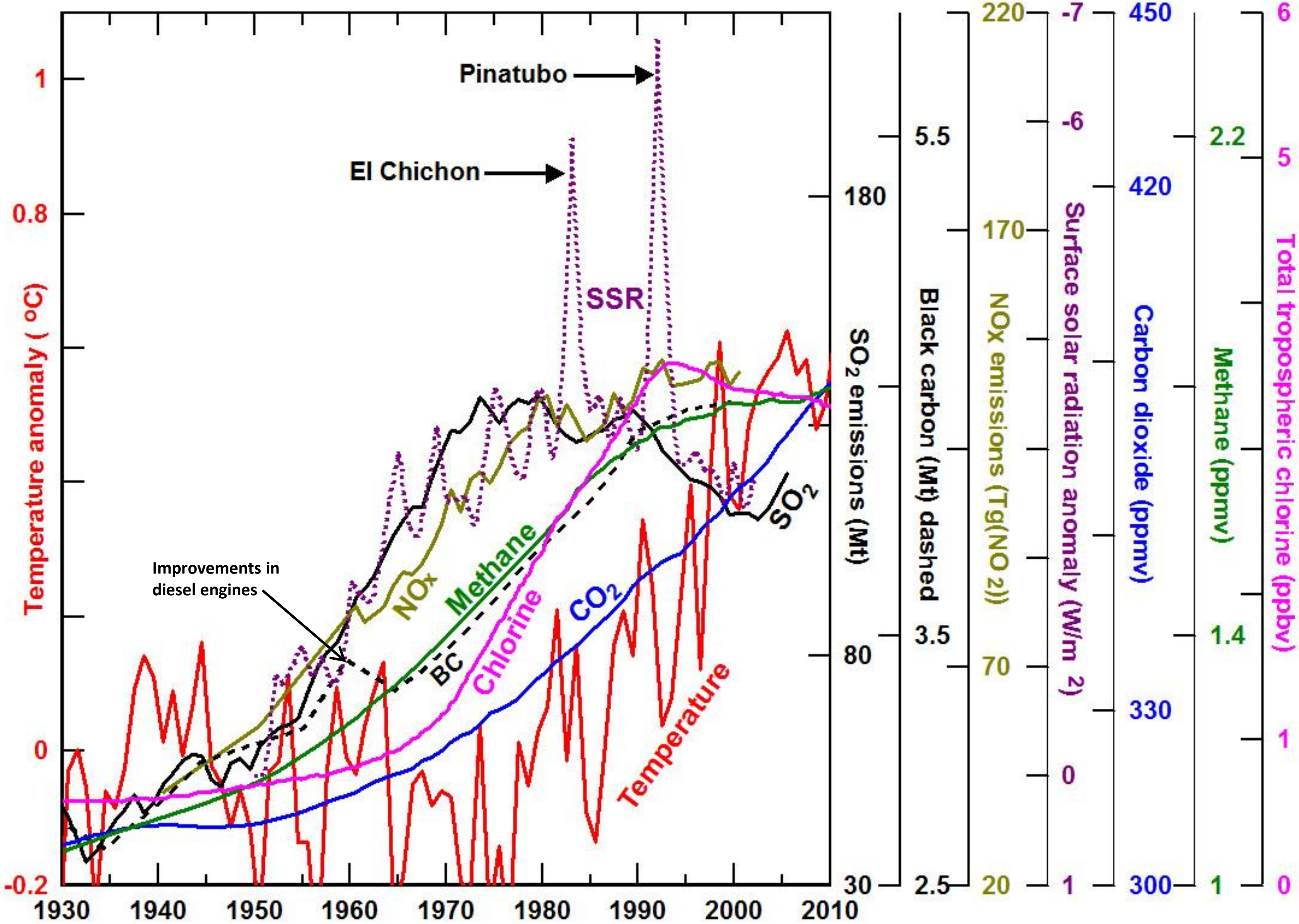
Similarly for NO_x, Methane, and Black Carbon



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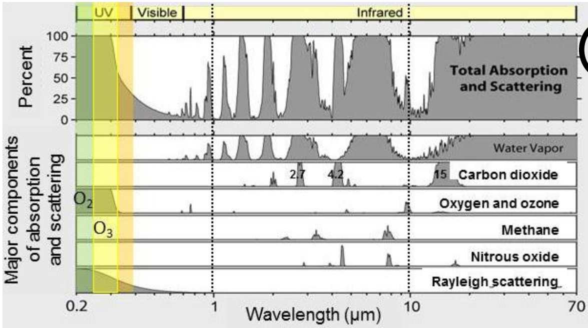
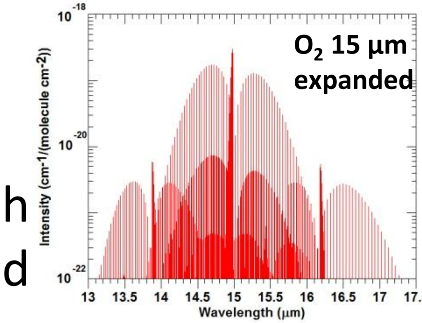
Absorption Without Photodissociation Does Not Appear to Cause Warming



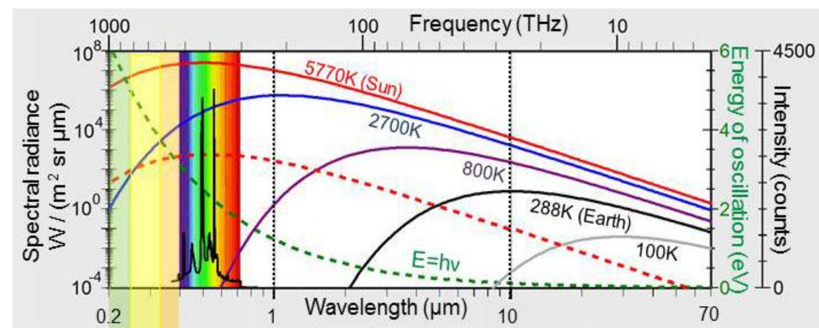
1 Greenhouse gases absorb energy in very narrow wavelength bands

along very narrow spectral lines such that not much energy is absorbed



The energy increases the intensity of the **vibrational and rotational kinetic energy** of the chemical bonds, but temperature in an ideal gas is proportional to average **translational kinetic energy**

2 Heat is broadband energy. An incandescent bulb radiates a broad spectrum (blue line) while a fluorescent bulb radiates narrow spectral peaks (black line). The incandescent bulb feels hot, the fluorescent cool.



3 Heat in solids flows from warm to cool. Radiation is absorbed by resonance and thus absorption can only occur from higher to lower spectral intensity. Our bodies absorb radiant heat, but we do not perceptively absorb radiant cold; instead we lose body heat more efficiently into a cold environment

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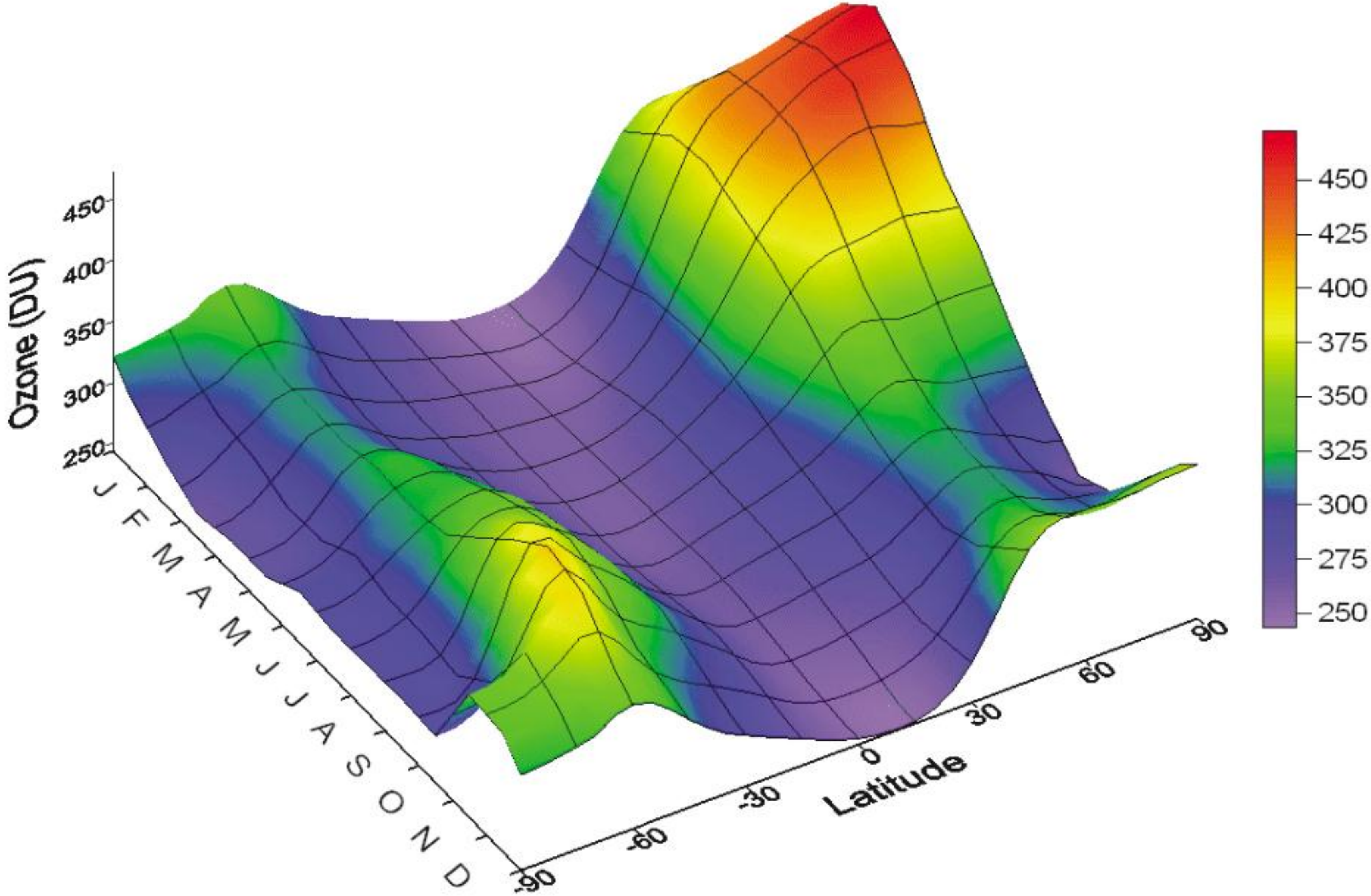
Conclusions

1. Ozone filters solar ultraviolet energy reaching Earth primarily in the 290-340 nm waveband where photodissociation of O_3 and NO_2 catalytically turns radiant energy into heat very efficiently
2. Total column ozone can increase as much as 20% in 6 hours, associated with a 5 km decrease in tropopause height
3. Short-term changes in ozone are closely associated with changes in weather
4. Long-term changes in ozone are closely associated with changes in climate
5. Anthropogenic chlorofluorocarbons depleted ozone ~3% in decades
6. Volcanic eruptions typically deplete ozone ~6% in a year
7. Large explosive volcanic eruptions form aerosols in the lower stratosphere that reflect, scatter, and absorb solar energy causing net cooling except in winter
8. Small effusive, basaltic fissure eruptions do not form aerosols, causing net warming
9. Ozone and ozone depletion are greatest in polar and mid-latitudes because of the Brewer-Dobson circulation and the fact that depletion is greatest at very cold temperatures especially related to polar stratospheric clouds
10. Extreme ozone depletion in 2011-2012 is closely associated in space and time with record warm temperatures and drought
11. Simple absorption by any gas of radiant energy not energetic enough to cause photodissociation does not appear to cause substantial warming
12. A detailed paper is in press and this poster and a video of northern hemisphere ozone for part of 2010 is available as an AGU ePoster

16 A Latitude-Longitude View of Monthly Mean Ozone



Surface plot of zonal monthly mean total ozone as a function of latitude and month estimated from ground-based data for the period 1964–80 (Fioletov, 2008). Compare to time plots in 10.